SPAWAR
Systems Center
San Diego

TECHNICAL REPORT 1803
August 1999

Designing a Display for the Area Air Defense Commander

The Role of 3-D Perspective Views and Realistic Track Symbols in Achieving Rapid Situation Awareness

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ADMINISTRATIVE INFORMATION

The work detailed in this report was performed for the Collaborative Technologies Project Team (Code D44215) of the Simulation and Human Systems Technology Division (Code D44) of the Command and Control Department (Code 40) of the Space and Naval Warfare Systems Center, San Diego, by Pacific Science and Engineering Group, Inc. as Delivery Order 46 under contract N66001–96–D–0048. Funding was provided by the Office of Naval Research under program element 0602233N and by SPAWAR PMW–467. This report covers work from October 1997 to March 1999.

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ACKNOWLEDGMENTS

The authors would like to extend their thanks to several individuals who contributed to the work described here. The project could not have been completed without the simulation programming efforts of Bryan Croft of SPAWAR Systems Center, San Diego, and the Motif interface programming efforts of Michael Madigan of the San Diego State University Foundation. We are grateful to Sylvia Saiz of San Diego State University Foundation, our research assistant, who ran the participants in the experiment and helped with the preparation of experimental materials. Dennis White of Basic Commerce and Industries, Incorporated was involved in developing the test scenario. Dr. Mark St. John at Pacific Science and Engineering provided helpful comments on an earlier draft of this report. The authors would also like to thank and acknowledge the following individuals who reviewed this report for technical accuracy: Dr. Michael B. Cowen and Michael L. Crowley from SPAWAR Systems Center, San Diego, and Jack Felloney of Techmatics, Inc. who reviewed the report on behalf of the AADC program office (PMS–467).

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EXECUTIVE SUMMARY

The Area Air Defense Commander (AADC) plans, coordinates, and executes air defense operations in a theater of operations. This responsibility requires a clear tactical picture of friendly and hostile forces and their capabilities. A new display has been prototyped for this purpose (figure 1). This prototype display has a three-dimensional (3-D) perspective format and uses novel volumetric (realistic) symbols. It has been touted as enabling users to become more rapidly aware of the tactical picture than a comparable two-dimensional (2-D) display. This study addresses two questions:

1. Does the 3-D display format promote more rapid Situation Awareness (SA) than a conventional 2-D display format?

2. Do the new detailed 3-D volumetric realistic symbols enhance performance over their more conventional non-realistic counterparts?

Three participant groups observed a 9-minute scenario in three different ways. The first group saw the scenario in a 3-D perspective view with realistic symbols. The second group saw a 2-D top-down view with realistic symbols. The third group saw a 2-D top-down view with conventional (non-realistic) symbols. The scenario was stopped every 30 seconds in each condition and an online questionnaire assessed participant SA attributes of depicted tracks.

FINDINGS

- Participants became increasingly aware of the track identities over time, but they had difficulty remembering the spatial attributes of those tracks.

- 2-D SA was initially 2.5 times higher than 3-D SA and remained significantly higher for the first 4 minutes.

- 3-D SA increased six times faster than 2-D SA for the first 5 minutes.

- Overall SA was equivalent for 2-D and 3-D after 9 minutes.

- 3-D was superior to 2-D for the attributes of altitude (4 times) and attitude (20 times).

- Realistic symbols were superior (two times) to non-realistic symbols for the heading attribute.

- Participants found it harder to learn realistic symbology.

CONCLUSIONS

- 2-D top-down display with conventional (non-realistic) symbols provided superior SA during the first 4 minutes.

- 3-D displays with realistic symbols provided superior SA for altitude, attitude, and heading attributes.

RECOMMENDATIONS

- Consider using 2-D top-down displays with conventional (non-realistic) symbols when very rapid SA is necessary.
- Consider using 2-D or 3-D realistic symbology when rapid heading appreciation is necessary.
- Consider using 3-D displays when rapid altitude and attitude appreciation outweighs other factors.

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INTRODUCTION

The Area Air Defense Commander (AADC) plans, coordinates, and executes air defense operations in a theater of operations. This responsibility requires a clear tactical picture of friendly and hostile forces and their capabilities. A new display has been prototyped for this purpose (figure 1). This prototype display has a three-dimensional (3-D) perspective format and uses novel volumetric (realistic) symbols. It has been touted as enabling users to become more rapidly aware of the tactical picture than a comparable two-dimensional (2-D) display. This study addresses two questions:

1. Does the 3-D display format promote more rapid Situation Awareness (SA) than a conventional 2-D display format?
2. Do the new detailed 3-D volumetric realistic symbols enhance performance over their more conventional non-realistic counterparts?

Figure 1. Screenshot from early version of AADC display prototype showing its realistic symbols in 3-D.

2-D VERSUS 3-D DISPLAY FORMAT

Conventional 2-D "bird's eye" displays represent two dimensions of the earth's surface and leave the third dimension (altitude) implicit. 3-D perspective displays, on the other hand, try to show the third dimension as well by depicting the perspective projection of an air space from a certain point of view above the ground plane onto the display screen (e.g., Ellis, McGreevy, and Hitchcock, 1987).

Why consider changing from a 2-D to a 3-D perspective display format? There are four main reasons. The first reason is to present users with a visual representation of depth on their inherently flat 2-D displays. Second, 3-D displays may be more natural for users. As we view objects, our retinal images are perspective projections of the world, so perspective displays may be inherently more ecologically plausible (Warren and Wertheim, 1990). Others have argued that because we plan,

perceive, and act in a 3-D environment, the integrated format of 3-D displays should make them easier to operate (Wickens, 1992). Third, users want 3-D displays. Users preferred the AADC prototype display during operational trials (Kramer, Hontz, and Broyles, 1995[1], cited in Schiller, Mitchell, and Bemis, 1998[2]). Fourth, and most importantly, some argue that 3-D displays give users a clearer picture of battlefield tactical information than conventional 2-D displays (e.g., Dennehy et al., 1994).

By conveying all dimensions of space directly, 3-D displays may provide a clearer picture because users are saved from having to slowly search through text boxes of airtrack attributes found on conventional 2-D displays (Dennehy et al., 1994). Supporting this notion, Baumann, Blanksteen, and Dennehy (1997) showed that users found descending planes more rapidly in a 3-D perspective view display than in a 2-D top-down display. This finding was no surprise to expert users. Eddy, Kribs, and Cowen (1999) asked surface warfare operators what they thought the limitations of the current displays were and what they want included in the next-generation tactical displays. They reported that the experts rated the everyday task of recognizing and classifying elements of air, surface, and subsurface threats as very difficult with existing display technologies. One respondent expressed the following: "We hate digital readouts because it takes longer to read and it doesn't tell a story." Most respondents indicated a need for a console "representing these sort of things in some other visual way that more intuitively paints a picture."

Despite these cogent arguments for 3-D, we should also look at the disadvantages. It may not be wise to base decisions on the fact that people like the look of 3-D displays. We know that user preference and performance do not always correlate well (Bailey, 1993). In fact, sometimes users want what is not best for them (Andre and Wickens, 1995). For example, Carswell (1991) showed that people rate 3-D graphs and bar-charts as more impressive than 2-D when at the same time they were less accurate at telling what the data depicted in 3-D compared to 2-D. There is a big price to pay when one moves from 2-D to 3-D. When a third dimension is represented in a 2-D space, attributes along all three dimensions become ambiguous in the following ways:

1. They are prone to distortion. To perceive the 3-D arrangement of any scene, the visual system must perform "reverse-optics" to figure out what objects plausibly gave rise to the retinal images of that scene. This is difficult because many different possible 3-D worlds can produce the same retinal images. The visual system must make its best guess as to what goes where. In 2-D displays, everything is put in the background plane. In 3-D displays, distortions readily occur because it is difficult to correctly place objects along the line of sight. There is usually only a restricted set of depth cues available to facilitate correct assignment. Additional depth cue features that disambiguate depth, such as drop-lines or drop-shadows from an aircraft to the ground plane, uniquely specify 2-D location (Wickens, 1992). The AADC prototype display uses drop-shadows.

2. They are prone to clutter. Use of drop-shadows or other augmentations to clarify depth increases the number of symbols in the display. These augmentations only work if users can maintain

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[1] Kramer, T. R., E. B. Hontz, and J. W. Broyles. 1995. "Force Threat Evaluation and Weapons Assignment (FTEWA) System Operational Suitability and Human Factors Evaluation for USS *Normandy* (CG60) Adriatic Seas Red Crown Operations. Internal documentation. Human Systems Interface Technology Research, Code D44215, SSC San Diego, CA.

[2] Schiller, E., C. Mitchell, and S. Bemis. 1998. "AADC 3-D Perspective Display Evaluation: Study on Resolution and Monitor Type." Internal documentation. Human Systems Interface Technology Research, Code D44215, SSC San Diego, CA.

"perceptual links" between them and the symbols for the aircraft. In dense displays, users may have too many links to remember them all. Baumann et al. (1997) found it surprising that users failed to find the last couple of descending planes in a high-density AADC prototype-like simulation when compared with 2-D control displays. Burnett and Barfield (1991) found that a 3-D advantage over 2-D for low-density displays disappeared at higher densities.

3. They are poor for precision tasks. St. John and Cowen (1999) recently showed that although 3-D displays conveyed shape well, they were poor for tasks that required them to determine distances and directions between objects in 3-D. An AADC may not need precise spatial information, but must have a good understanding of the tactical picture.

4. Realistic icons do not scale well. Emmert's law of size constancy states that perceived distance is directly related to image size (see McKee and Smallman, 1998). In a 3-D display, distant icons should be smaller, but they will quickly get too small to be recognized. Following Emmert's law, falsely scaled icons may be perceived at the wrong depth in this display.

5. They are not isotropic. 2-D displays give an equal display area to an equal physical area on the ground plane. In this sense, they are said to be isotropic. However, because of imaging geometry, 3-D perspective displays must give less display area to regions near the horizon and vanishing point. In addition to a loss of fidelity, this makes clutter even more problematic because far objects and their drop-shadows will be packed into an even smaller display area.

Consequently, current research has been equivocal at documenting actual performance improvements with 3-D displays. Across an array of tasks, some studies have found 3-D benefits over 2-D (Andre et al., 1991; Bemis, Leeds, and Winer, 1988; Burnett and Barfield, 1991; Ellis et al., 1987; Haskell and Wickens, 1993; VanBreda and Veltman, 1998; Wickens and Prevett, 1995; Ware and Franck, 1994; Baumann et al., 1997), some have found rough parity (Wickens, Liang, Prevett, and Olmos, 1996; Wickens and May, 1994), and some have found 2-D superior to 3-D (Boyer and Wickens, 1994; Boyer et al., 1995; Endsley, 1995a; O'Brien and Wickens, 1997; Wickens et al. 1995). Several factors contribute to this confusion: (1) different tasks and displays used in different studies, (2) 3-D displays typically different in the specification of imaging geometry and depth cues, and (3) comparisons between 3-D and 2-D displays not matched as attribute information.

TRACK SYMBOLS

In addition to the issue of 2-D versus 3-D, we must know how to best represent the military symbology in the display. As noted above, the AADC prototype display uses realistic 3-D volumetric icons to represent each type of aircraft and ship. These icons seem intuitive, but do they lead to better SA? Consider the various depictions of a bomber in figure 2. The left of figure 2 shows a 3-D realistic rendition of a bomber. The center shows a realistic bomber in 2-D, and the right shows a conventional (non-realistic) symbol for a bomber. Which is better? Florence and Geiselman (1986) examined visual search for symbols depicted realistically (iconically) versus non-realistically (symbolically) on a 2-D display. They found a slight advantage for iconic presentation.

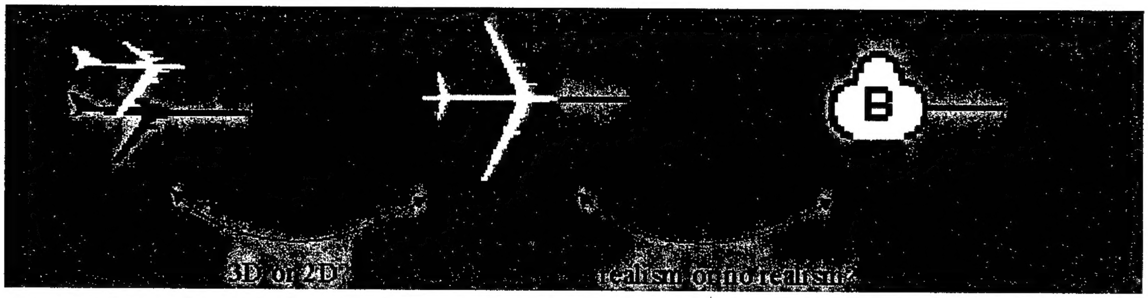

Figure 2. Three different ways of depicting bomber headed east on display. Bomber depicted realistically in 3-D as used in AADC prototype display (left), realistically in 2-D (center), and symbolically in 2-D (right) (e.g., Mil-Std-2525B).

OBJECTIVE

This objective this study was to test whether a 3-D display format promotes more-rapid SA than a conventional 2-D display format and if realistic symbols are associated with better performance than conventional 2-D symbols.

APPROACH

We employed three different display conditions: (1) a 3-D realistic condition, similar to the AADC prototype display, with realistic icons, (2) a 2-D realistic condition that uses realistic icons on a 2-D display, and (3) a 2-D non-realistic condition that uses conventional symbols on a 2-D display. We are concerned with how the conditions affect element perception in a depicted situation (i.e., how it affects their SA). SA has been defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status on the near future" (Endsley, 1988, p. 97). It is considered vital for good performance in Air Traffic Control (ATC) tasks and air combat simulations (Endsley, 1995a). SA is closely related to the mental model that a user develops of the display information (Mogford, 1997; Sarter and Woods, 1991). Endsley (1995b) has proposed the following three-step model of SA: (1) successful SA involves perceiving the current situation elements (level 1 SA), (2) comprehending how those elements figure into the current situation (level 2 SA), and (3) figuring how the future situation may develop from the present one (level 3 SA). Level 1 SA is the most-critical SA level. Without correct perception of what is depicted in a display, decision-making will be based on faulty or sketchy information. We focused on Level 1 SA.

Various ways of measuring SA have been proposed. Among the better techniques are online questionnaires. Questionnaires are good in that they are objective and are touted as minimally corrupting the awareness that they are intended to measure (Endsley, 1995a). They have been used successfully in several studies. Marshak et al. (1987) first used questionnaires when they queried participants about various aspects of aircraft location and heading during freeze-frames in an ATC simulation. Variants of this technique were used in subsequent studies in ATC and air combat simulations (Endsley, 1995a; Fracker, 1990; Mogford, 1997; Baumann et al., 1997). Online questionnaires were used in the study described in this report.

METHOD

PARTICIPANTS

The participants were 39 people at Space and Naval Warfare Systems Center, San Diego (SSC San Diego) employed as researchers, students, technicians, or military staff. There were nine active duty military personnel[3] and 36 participants were male. Participants were equally assigned to the three conditions based on experience with 3-D displays and military symbol sets. All subjects had prior experience with computer displays. All but five subjects had prior experience with military symbol sets and 17 subjects had no experience with 3-D displays. Ages varied from 20 to 65 with a mean of 41.

APPARATUS

Simulations were run on a Silicon Graphics Indigo 2™ workstation and shown to participants on a high-resolution, wide-format computer monitor. The simulation display dimensions were 8 inches high by 12 inches wide. Probe questionnaires were shown on a second adjacent monitor. Participants were seated 19 inches in front of these two displays, and they viewed them with both eyes open in the dimly illuminated, low-glare, experimental room. The mean display luminance was approximately 50 cd/m^2. Participants interacted with the computer displays through a computer mouse. Color printouts of the military symbols used in the simulations were placed to the left of the apparatus.

PROCEDURE

There were four phases to the procedure:

Phase 1. When the participants arrived, they were screened for normal vision. Two tests were given. They were screened for visual acuity with a Snellen acuity chart. We set 20/40 as the criterion subjects needed to pass for further participation (comparable to the California Department of Motor Vehicles' legal requirement to be able to drive). Participants were then screened for normal color vision with the 14 standard Ishihara color plates.

Phase 2. Participants passing the Phase 1 screening were then trained on one of three symbol sets. These sets were the 2-D non-realistic symbol set (figure 3), the 2-D realistic set (figure 4), and the 3-D realistic symbol set (figure 5). There are four symbols for each platform. In the figures, platforms are grouped into four categories (ground, air, surface, and sub-surface). The platform symbols can be one of four colors on track friendliness (blue for friendly, red for hostile, green for neutral, and yellow for unknown). In addition to color, symbol shape varied by friendliness in the 2-D non-realistic set (friendly blue symbols were circular, red hostile symbols were diamonds, etc.). Other differences among the three symbols sets, apart from the obvious symbol shape differences, were that there were three extra air platforms for fighters (not actually used in the scenarios) in the realistic sets, and the color for "friendly" was white instead of blue in the realistic sets (to mimic the AADC prototype display coding).

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[3] The active military did not score differently on average from other subjects in any of the experimental conditions.

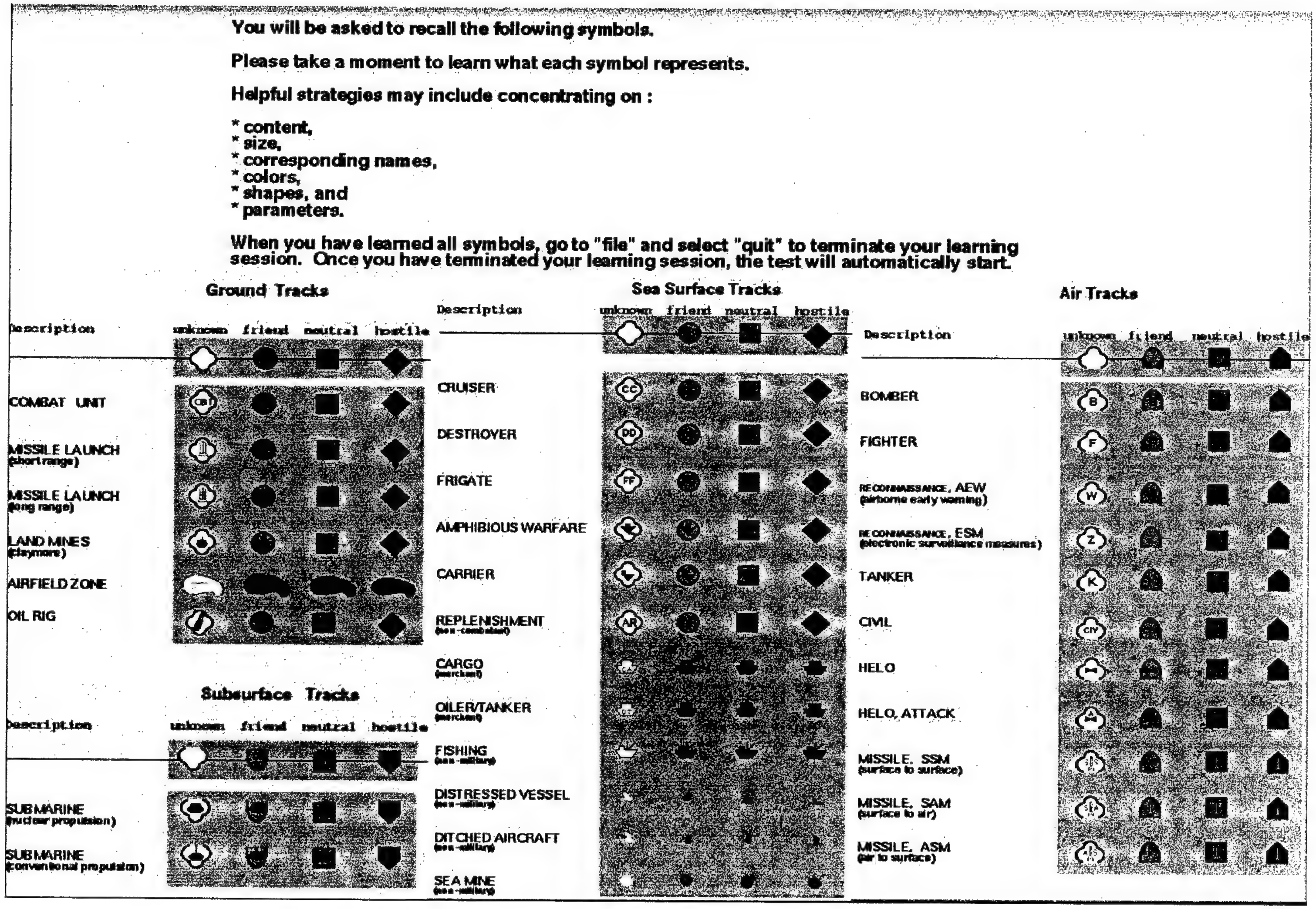

Figure 3. Symbol set for 2-D non-realistic condition. Set includes 31 different platforms (in rows) organized into four track categories (ground, subsurface, sea surface, and air). Columns show four possible track colors. Color shows friendliness (unknown, friendly, neutral, and hostile). For military platforms, friendliness is also coded by track shape (e.g., neutrals are square). The symbol set is part of Mil-Std-2525B.

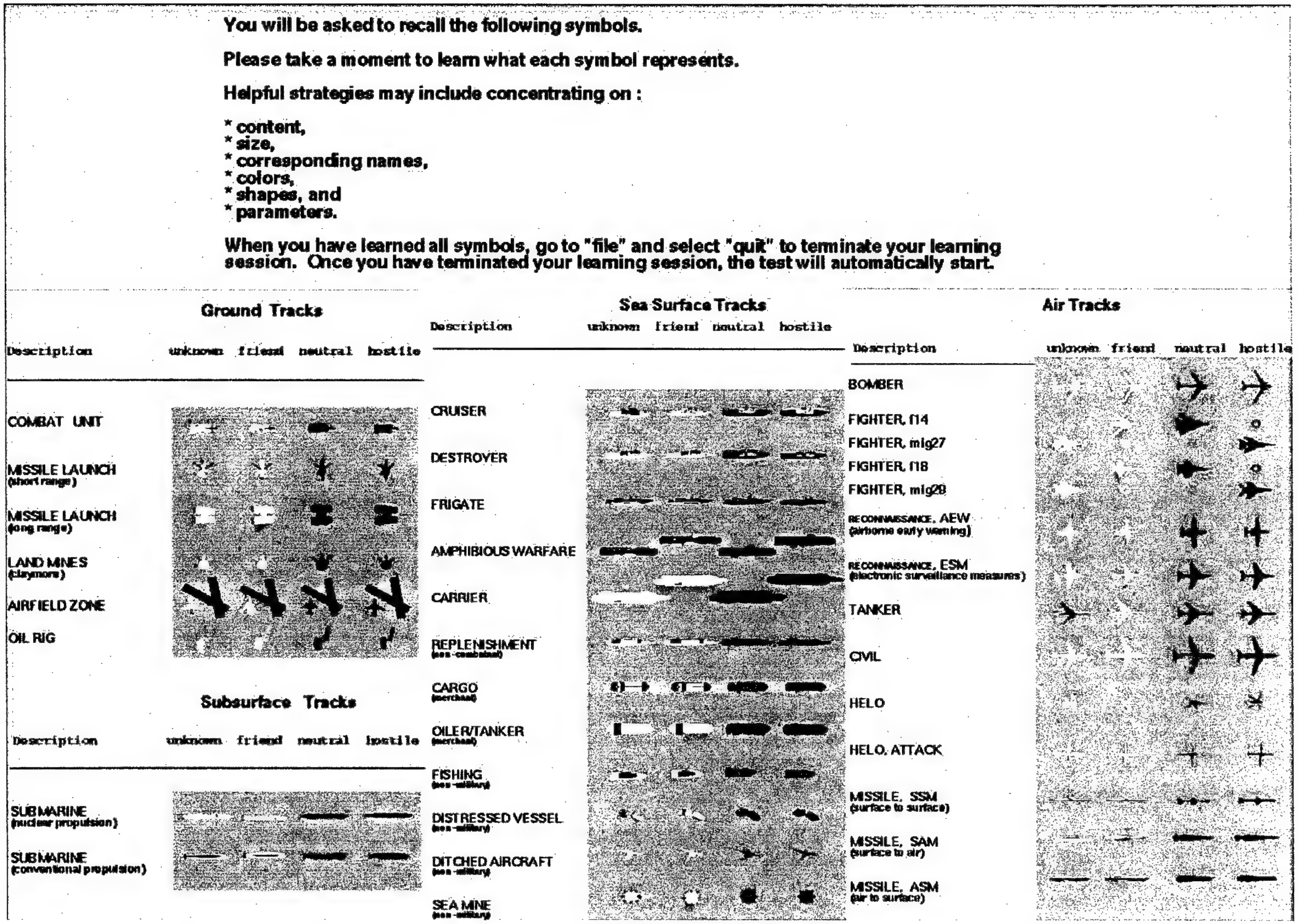

Figure 4. Symbol set for 2-D realistic condition. Set includes 34 different platforms (in rows) organized into four track categories (ground, subsurface, sea surface, and air). Columns show the four possible track colors. Color depicts friendliness (unknown, friendly, neutral, and hostile).

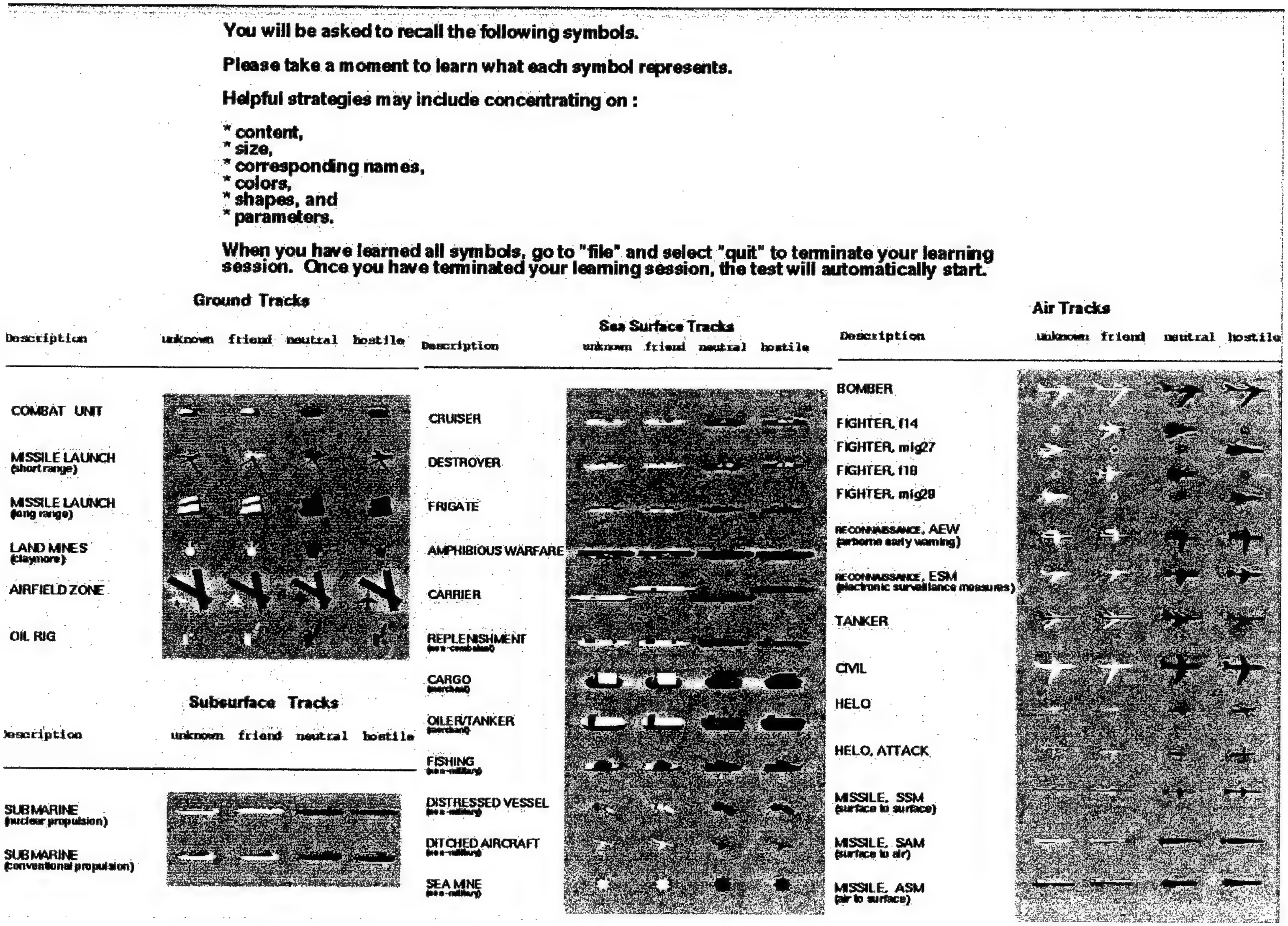

Figure 5. Symbol set for 3-D real condition. Set includes 34 different platforms (in rows) organized into four track categories (ground, subsurface, sea surface, and air). Columns show four possible track colors. Color depicts friendliness (unknown, friendly, neutral, and hostile).

We chose the Mil-Std-2525 set (comparable to NATO symbology) for our conventional 2-D non-realistic symbol set because individual platform types are represented in Mil-Std-2525. The Mil-Std- 2525 symbol set enabled us to compare platform identification across the different sets. After participants spent 5 minutes learning their symbol set, they were tested on symbol identification. The symbol set was replaced on the computer display by a questionnaire containing 40 questions, with each question asking about a different track. The questions represented all platform types. Participants were instructed to identify the track's platform correctly from drop-down menus. Time to complete the questionnaire was recorded, as were total errors. If a participant failed to correctly identify a track after two wrong guesses, that person moved on to the next question. When a participant completed the questionnaire, the participant was given feedback on incorrect answers with a large color printout of the symbol set they had just learned. This printout was left visible to the participant for the remainder of the experiment. The participant was told to use the printout if a symbol was forgotten later.

Phase 3. Participants were then presented a practice simulation. This simulation depicted a collection of 21 different tracks arrayed on a mixed terrain map of a peninsula surrounded by water. Besides track type and friendliness, each track possessed up to four spatial attributes. These spatial attributes were heading and speed (for tracks that could move), and altitude and attitude (for air tracks). These spatial attributes were depicted in different ways in the three different display conditions. Table 1 shows the coding scheme.

Table 1. Spatial track attributes by condition.

Spatial Attribute	2-D Non-Realistic	2-D Realistic	3-D Realistic
Altitude	Hooking	Hooking	Explicit + hooking
Attitude	Hooking	Hooking	Explicit + hooking
Speed	Leader length + hooking	Leader length + hooking	Leader length + hooking
Heading	Leader orientation + hooking	Explicit + hooking + leader orientation	Explicit + hooking + leader orientation

For example, in figure 2, tracks for a bomber are depicted. The bomber is of unknown friendliness, headed east at medium speed and at low altitude. A yellow realistic icon pointed to the right depicts the 3-D realistic bomber (figure 2, left) and it is flying level. Directly under the icon is a black drop-shadow of a bomber on the ground plane pointed to the right with a medium-length black leader also pointed right. The 2-D realistic bomber (figure 2, center) is depicted as a realistically shaped yellow bomber (seen from above) pointed to the right with a medium black leader off its nose. The 2-D non-realistic bomber (figure 2, right) is depicted with a Mil-Std-2525B symbol, a 'B' in a yellow-filled cloverleaf with a medium-length black leader protruding from its right-hand side. To discover the air track altitude and attitude for conditions other than 3-D, the user had to hook the track. Users hooked the track by rolling the mouse pointer over a track to display a text box in red that listed all selected track attributes. They hooked the same way across all three conditions. Users kept the text box on the display by clicking the mouse when the text box was present. This turned the text white. The mouse pointer could then be rolled away to do the same with other tracks. As multi-

ple text hooks can cause clutter, participants could remove a white text box by clicking on it and then moving the cursor away from the track.

The spatial track attributes were subdivided into a smaller number of ordinal categories to make it both easier for participants to remember them and for us to ask questions about them. Attitude was categorized as descending, level, or ascending. Speed was slow, medium, or fast. Heading was N, NE, E, SE, S, SW, W, or NW. Altitude was high, medium, or low. Appendix A discusses the assignment of altitude to air tracks.

During the practice simulation, a friendly missile was fired towards a hostile missile battery to the north of the peninsula. Figure 6 shows a screenshot of the beginning practice simulation in the 2-D non-realistic condition. The display updated every 4 seconds and all mobile tracks moved by an amount proportional to their speed leaders. Stationary tracks, those lacking speed leaders, did not move.

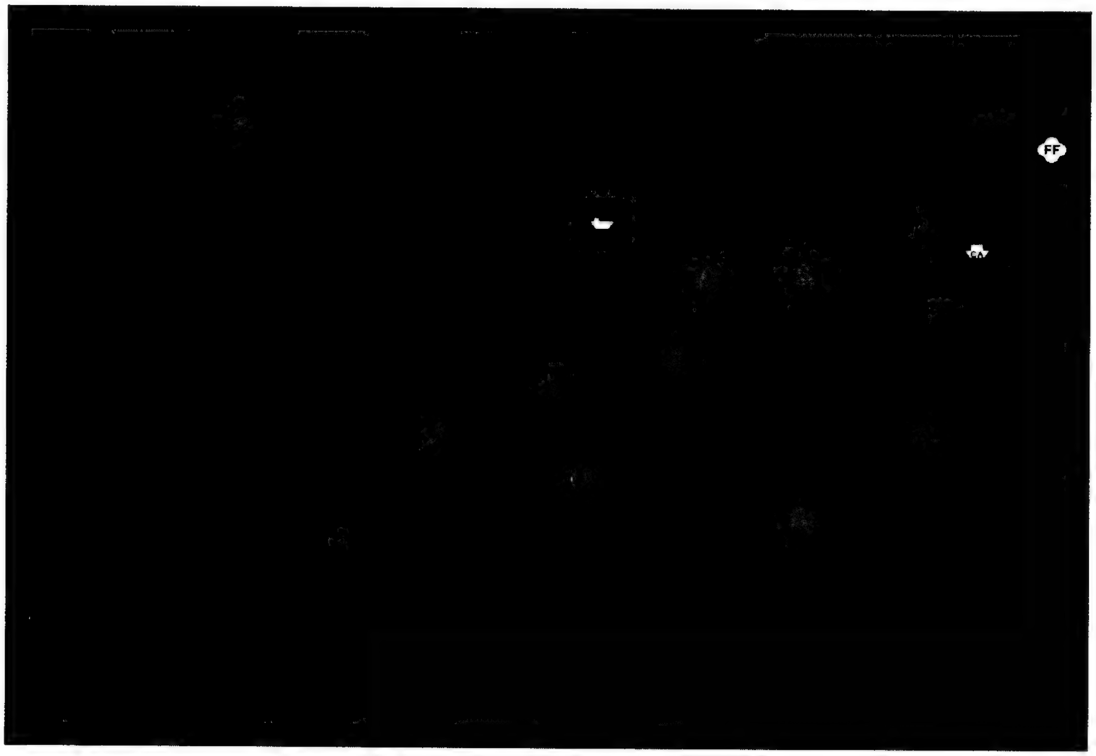

Figure 6. Screenshot from beginning of practice simulation for 2-D non-realistic condition.

To assess SA during the practice simulation, every 30 seconds, the simulation froze and numbered black circles randomly replaced four track[4] symbols. Participants were then asked about their recollection of the four track attributes. On the second computer monitor, four questionnaires were displayed corresponding to the four covered-up tracks. Each participant had to select what platform the track depicted, its friendliness (color), and its spatial attributes (altitude and attitude for air tracks, heading and speed for moving tracks). The questionnaires were presented as a series of button boxes that the participant could fill in by clicking next to an item. A "do not know" box was available to click if participants felt that they could not recall any details, or they could leave parts of the questionnaire blank. Participants were encouraged to fill in as much of the questionnaire as possible. They were urged not to guess if they did not know the answer. Appendix B shows a sample questionnaire.

For the first two probe sessions during the practice session, the experimenter gave the participant feedback on the procedure of looking at the simulation and then answering the four questionnaires to facilitate learning. After that, the participants continued to acquaint themselves with the task uninterrupted.

Phase 4. After learning the symbol set and participating in a practice simulation, subjects were finally run in the main experimental simulation. This simulation depicted 45 tracks arrayed on a mixed terrain map of the Strait of Hormuz in the Persian Gulf. In this scenario, a hostile Surface-to-Air Missile (SAM) is fired towards friendly forces and is shot down by a friendly F-14 fighter. There were 19 different platform types represented in the scenario. Figure 7 shows a probe screenshot from near the beginning of this scenario for the 3-D condition. Figure 8 shows the exact same moment in the scenario for the 2-D real condition that figure 7 shows, and figure 9 shows the same moment in the 2-D non-real condition. Comparison between figures 7 and 8, therefore, shows the differences of depicting the display in 3-D or 2-D. Comparison between figures 8 and 9 shows the differences of depicting tracks realistically or non-realistically.

The simulation was probed 18 times. It was exactly like the practice simulation except that it was longer and the computer recorded response data. The average time to complete all four phases of the experiment was about 1.5 hours.

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[4] Tracks in the 3-D condition had their symbols replaced by black spheres if they were non-air tracks or they had their drop-shadows on the ground plane replaced with black circles if they were air tracks. We probed this way in order not to 'tip-off' participants that we were testing them on an air track by showing them a black sphere floating in mid-air.

Figure 7. Screenshot from 3-D real condition. Camera angle was 25° above ground plane. This shot was taken during SA probing. Participants had to recall attributes of four tracks replaced with numbered black circles.

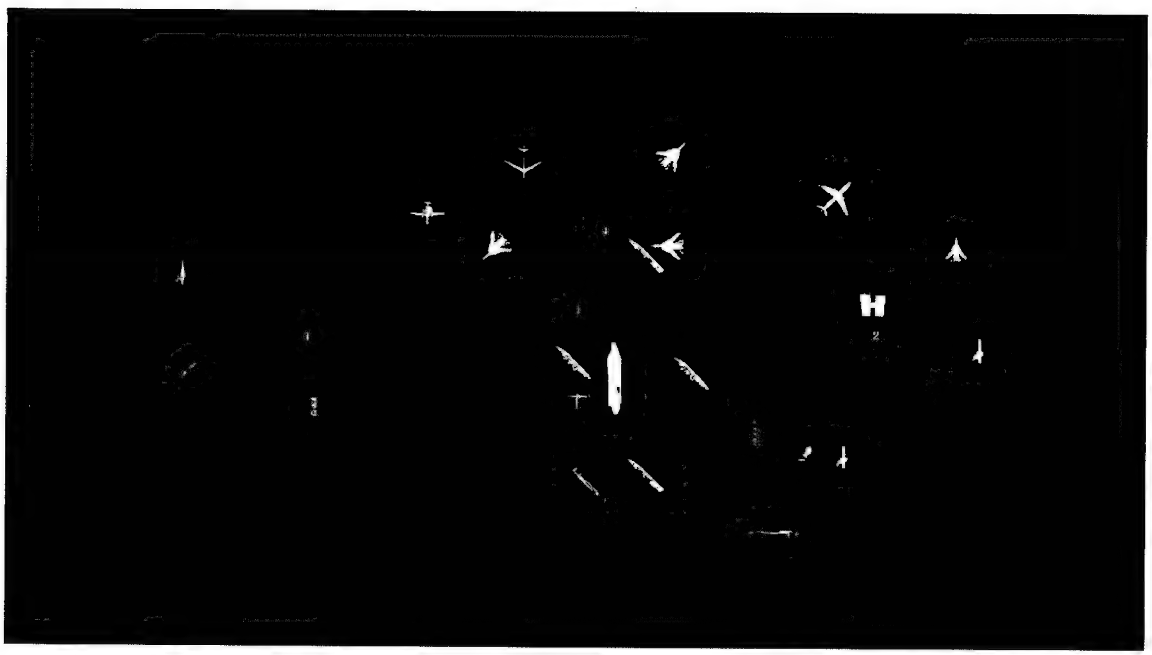

Figure 8. Screenshot from 2-D real condition. Shot taken from exactly same moment in scenario as that shown in figure 7.

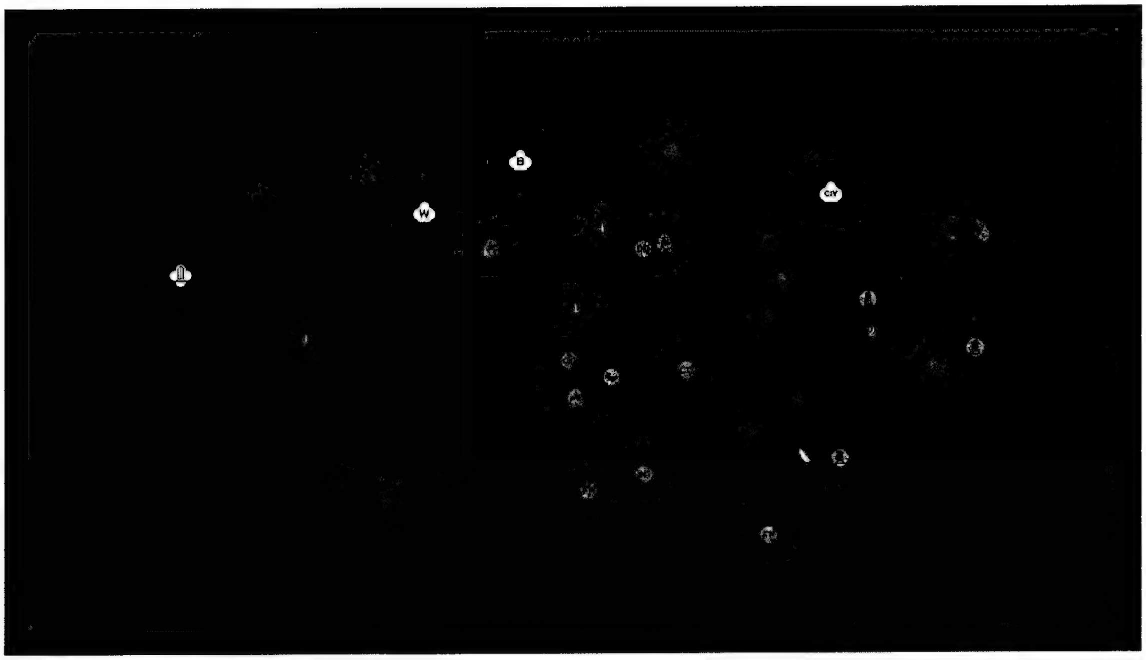

Figure 9. Screenshot from 2-D non-real condition. Shot taken from same moment in the scenario as that shown in previous two figures.

DESIGN

Each subject participated in only one of the three display conditions: the 2-D non-realistic, the 2-D realistic, or the 3-D realistic condition. Participants answered questions in 18 probe sessions. Each probe contained four questionnaires that asked questions about six track attributes. Two track attributes involved identification (platform and friendliness) and four attributes were spatial (heading, altitude, attitude, and speed).

RESULTS

SYMBOL SETS

In Phase 2 of the procedure, participants were given 5 minutes to study the symbol sets. We timed their completion of the questionnaire that probed their knowledge of the symbol set that they just viewed. We also recorded the errors they made on the questionnaire. These data are summarized in table 2.

Participants remembered fewer of the realistic symbols than the non-realistic symbols. A one-way analysis of variance (ANOVA) revealed that the platform identification errors differed significantly by display condition ($F(2,38) = 6.45$, $p < .05$). Pair-wise comparisons between the mean platform identification errors revealed that participants who had learned the 2-D non-realistic symbol set made fewer platform identification errors than those who learned the 2-D realistic symbol set ($p < .005$). Participants were slower with the realistic symbols, and more friendliness identification errors occurred in the 3-D realistic condition, but neither of these results reached statistical significance.

Table 2. Mean questionnaire completion times, platform identification errors, and friendliness identification errors from training sessions for three symbol sets. Standard mean errors indicated (i.e., ± error).

Condition	Mean Questionnaire Completion Time (min)	Mean Platform Identification Errors	Mean Friendliness Identification Errors
3-D realistic	12.3 ±1.7	12.5 ±3.0	1.5 ±0.4
2-D realistic	13.9 ±1.4	21.6 ±3.8	0.6 ±0.2
2-D non-realistic	9.4 ±1.2	6.4 ±2.5	0.6 ±0.3

GROWTH OF SITUATION AWARENESS WITH TIME

Did 3-D displays promote more-rapid SA than 2-D displays? Figure 10 shows SA growth with time, where SA is defined as the percentage of all correctly answered questions about all six attributes of the probed tracks by a given probe session. To quantify SA growth, polynomial linear regressions (including linear and quadratic terms) were fit to the data for the three conditions in Figure 10. Table 3 shows the regression equations. All regression terms in table 3 were statistically significant except for the quadratic term calculated for the 2-D non-realistic condition.

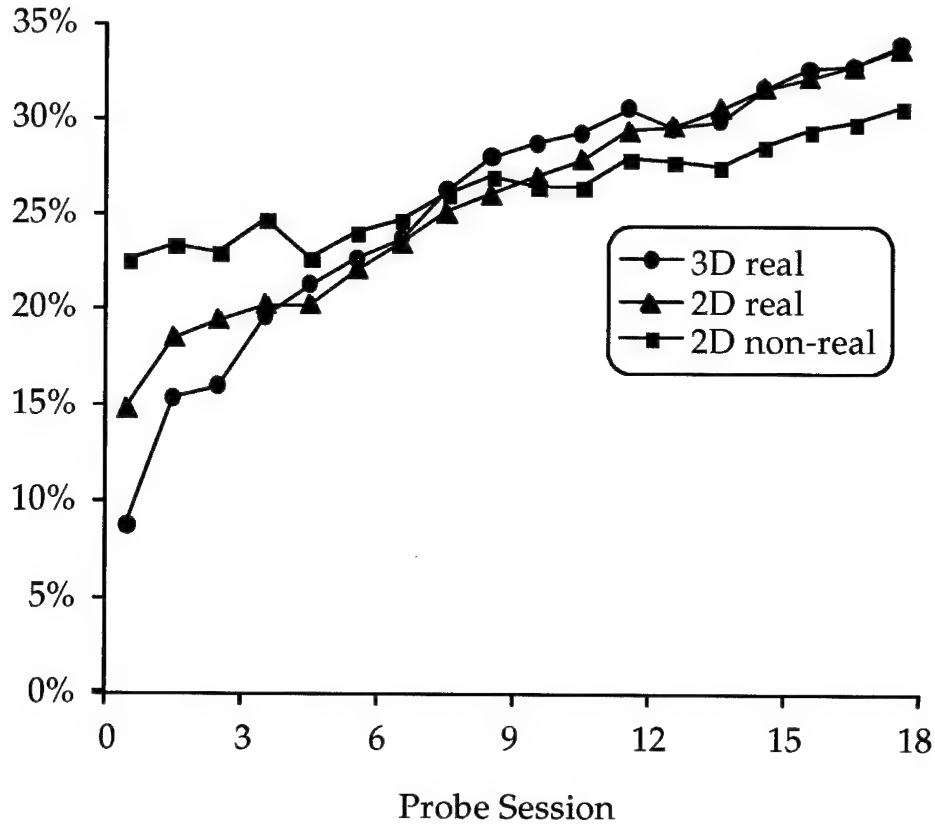

Figure 10. SA growth for three conditions over time (the 18 probe sessions). Percent correct for all six track attributes over time is plotted cumulatively on y-axis.

Table 3. Regression equations and statistical significance of terms making up regression equations (figure 10).

Condition	Regression Equation	Significant Intercept?	Significant Linear Term?	Significant Quadratic Term?
3-D realistic	$SA = 8.4 + 2.8p - 0.082p^2$	Yes **	Yes **	Yes **
2-D realistic	$SA = 14.2 + 1.5p - 0.02p^2$	Yes **	Yes **	Yes **
2-D non-realistic	$SA = 21.8 + 0.46p$	Yes **	Yes **	No

** $p < .01$

SA growth has two components. There is the level SA reaches at a certain time and there is the rate of increased SA growth at that time. We can conveniently analyze these aspects of SA growth separately by using the regression equations.

We get the rate of SA increase with time by differentiating the regressions with respect to probe session, p. The 2-D non-realistic condition yields

$$dSA/dp = 0.46.$$

This means that for every probe session, p, SA increased by 0.46 percent. The 3-D realistic condition yields

$$\mathrm{dSA}/\mathrm{dp} = 2.8 - 0.164p^{\dagger}.$$

Thus, SA increased by nearly 2.8 percent for every probe session (nearly six times faster than for the 2-D non-realistic condition) over the initial probe sessions (when the rate of increase slowed as p increased). The 2-D realistic condition yields

$$dSA/dp = 1.5 - 0.04p.$$

The rate of increase of 2-D realistic SA, at initially 1.5 percent per probe session, was in-between that found for the 2-D non-realistic and 3-D realistic conditions.

We can find out what SA probe sessions increased fastest for the 3-D realistic condition over the other two conditions by solving simple algebraic inequalities. We find that 3-D realistic SA increased faster over the first 10 probe sessions than 2-D realistic SA by solving the expression, $2.8 - 0.164p > 1.5 - 0.04p$, for p. Similarly, 3-D realistic SA increased faster than the 2-D non-realistic during the first 15 probe sessions. Finally, 2-D realistic SA increased faster than 2-D non-realistic SA across all probe sessions.

In summary, SA increased faster for 3-D, but it did not rise to higher levels than 2-D. SA started at a lower level for 3-D than 2-D. By the last probe session, all the curves in figure 10 pinched together: 3-D realistic SA was 33.8 percent, 2-D realistic was 33.6 percent, 2-D non-realistic was 30.6 percent. Thus, SA starts at a lower level for the 3-D realistic display, grows faster with time than the other display types, and saturates at a level equivalent to the 2-D display variants by the end of the scenario.

TRACK ATTRIBUTES

The previous analysis grouped together all the information from the probe questionnaires into a gross SA measure. We now examine performance for the six different track attributes to see how they differed by display type. Figure 11 shows percent correct performance for the six attributes collapsed across all probe sessions. The attributes in figure 11 have been grouped into those attributes that reflected information about the identity of a track (platform type and friendliness) and those that dealt with the spatial attributes of a track (altitude, attitude, heading, and speed).

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† Differentiating the quadratic term of the regression doubles its value when calculating rate of increase.

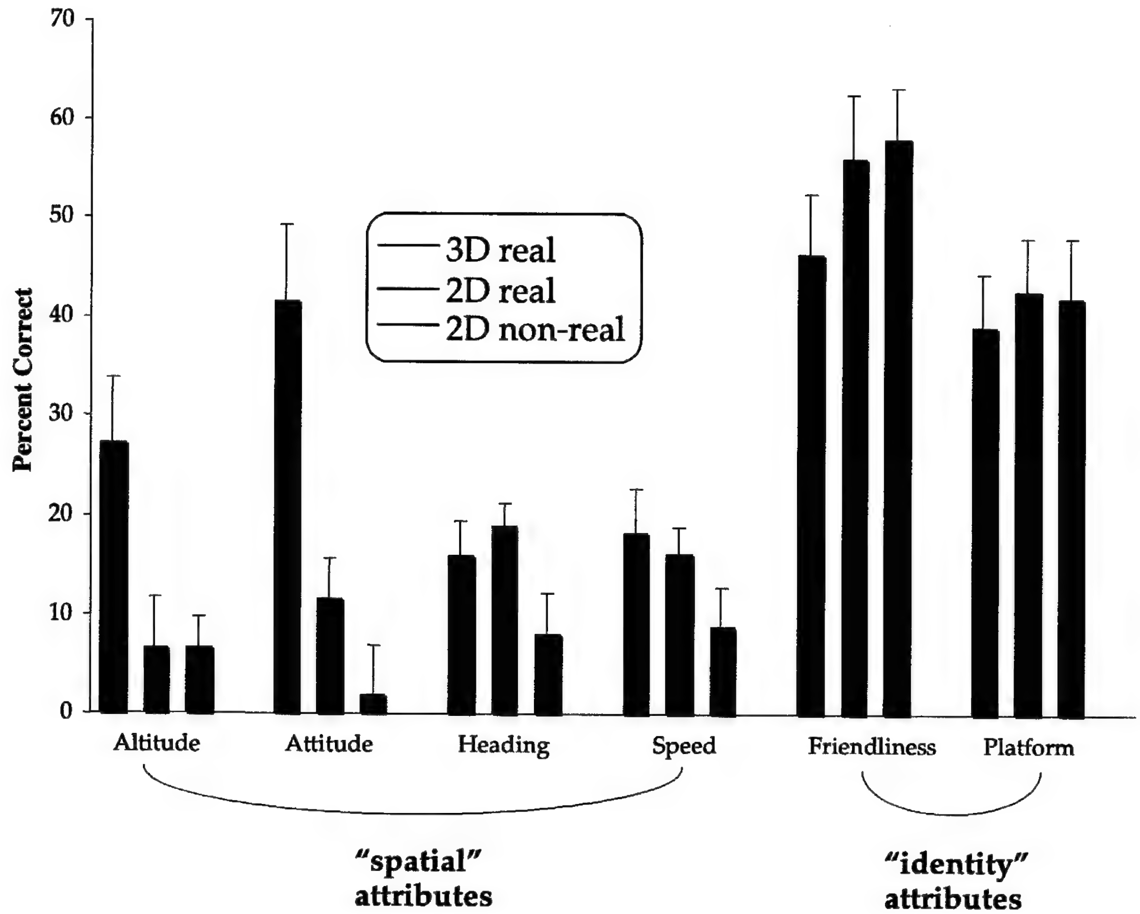

Figure 11. Percent correct performance for track attributes by condition. Data were collapsed across All the probe sessions. Error bars depict standard mean errors.

We ran a three-way split-plot ANOVA (six probe[5] x six attributes x three display types) to test for performance differences across display type. Table 4 shows the analysis results. Participants did not differ significantly in their awareness of the identity attributes for the different display types, irrespective of whether information was presented in 2-D or 3-D, realistically or symbolically. The spatial attributes tell a different story. Three of the four were significantly different. Table 5 shows how the spatial attributes were made known in the display. Superior coding schemes are marked with red ticks (|). Please note that a user can activate all spatial attributes for all conditions by hooking a track.

---

[5] Although there were 18 probe sessions actually tested, because of the quasi-random process of choosing which four tracks were probed on a given session, not all attributes were tested on each probe session (e.g., a probed oil rig lacks heading, speed, altitude, and attitude). These missing data necessitated collapsing adjacent probe sessions until all attributes were represented on each probe level. Collapsing three adjacent probe levels reduced missing data as a proportion of total data from 19 to less than 2 percent (the latter was replaced by appropriate means). Thus, there are six probe levels in the reported ANOVAs.

Table 4. Three-way ANOVA results: display type by track attributes across probe sessions.

Attribute Type	Attribute	Effect size (η^2)	df	F	Significant?
Spatial	Altitude	0.244	(2,36)	5.80**	Yes
Spatial	Attitude	0.386	(2,36)	11.31**	Yes
Spatial	Heading	0.180	(2,36)	3.95*	Yes
Spatial	Speed	0.003	(2,36)	.05	No
Identity	Friendliness	0.045	(2,36)	.85	No
Identity	Platform	0.007	(2,36)	.12	No

* $p < .05$
** $p < .01$

Altitude. There was a 3-D benefit for the altitude depiction. This was a substantial effect with performance four times better for 3-D. Post-hoc comparisons revealed that the 3-D realistic display was superior to both the 2-D non-realistic and 2-D realistic (p < .05 for both).

Attitude. There was a 3-D benefit for depicting attitude of air tracks. This was a massive effect; performance was 20 times better in 3-D realistic than 2-D non-realistic. Post-hoc comparisons revealed that 3-D realistic was superior to both the 2-D non-realistic and 2-D realistic (p < .05 for both).

Speed. Participants' awareness of the probed track speed in the different conditions was not significantly different. Speed was coded the same way in the different conditions by leader length (table 5).

Heading. There was a two-fold benefit for depicting heading realistically. Post-hoc comparisons revealed that both the 3-D realistic and 2-D realistic were superior to the 2-D non-realistic (p < .05 for both). As table 5 shows, heading was depicted by leader orientation in all three conditions, but in the realistic conditions it was also coded explicitly in the icon orientation on the display (things simply pointed in the direction they were heading).

Table 5. Spatial track attributes that supported better performance.

Spatial Attribute	2-D Non-Realistic	2-D Realistic	3-D Realistic
Altitude	Hooking	Hooking	Explicitl + hooking
Attitude	Hooking	Hooking	Explicitl + hooking
Speed	Leader length + hooking	Leader length + hooking	Leader length + hooking
Heading	Leader orientation + hooking	Explicitl + hooking + leader orientation	Explicitl + hooking + leader orientation

Red ticks indicate statistically superior performance.

PERFORMANCE BY ATTRIBUTE OVER PROBE SESSION

We can combine analysis elements of the two previous sections by now asking how performance varied for the different attributes over a probe session. There were six attributes times three display types across 18 probe sessions. Rather than show a cluttered graph with 18 curves, figure 12 shows the data with probe sessions collapsed into two groups (identity and spatial attributes) by condition. The figure shows that performance for the identity attributes differed considerably from the spatial attribute performance over time. Participants became increasingly aware of which tracks were depicted. The linear contrast in the three-way ANOVA confirmed this trend (F (1,36) = 117.40, $p < .01$). The linear contrast for the spatial attributes was also statistically significant (F (1,36) = 8.30, $p < .05$), but by a much smaller amount. Performance increased, on average, by 66 percent from the first to the last probes for the spatial attributes. In contrast, performance increased 127 percent for the identity attributes. For spatial attributes, performance in the 3-D condition was significantly better (F (2,36) = 4.62, $p < .05$) than the 2-D condition, in part because of better performance for attitude and altitude, as previously noted.

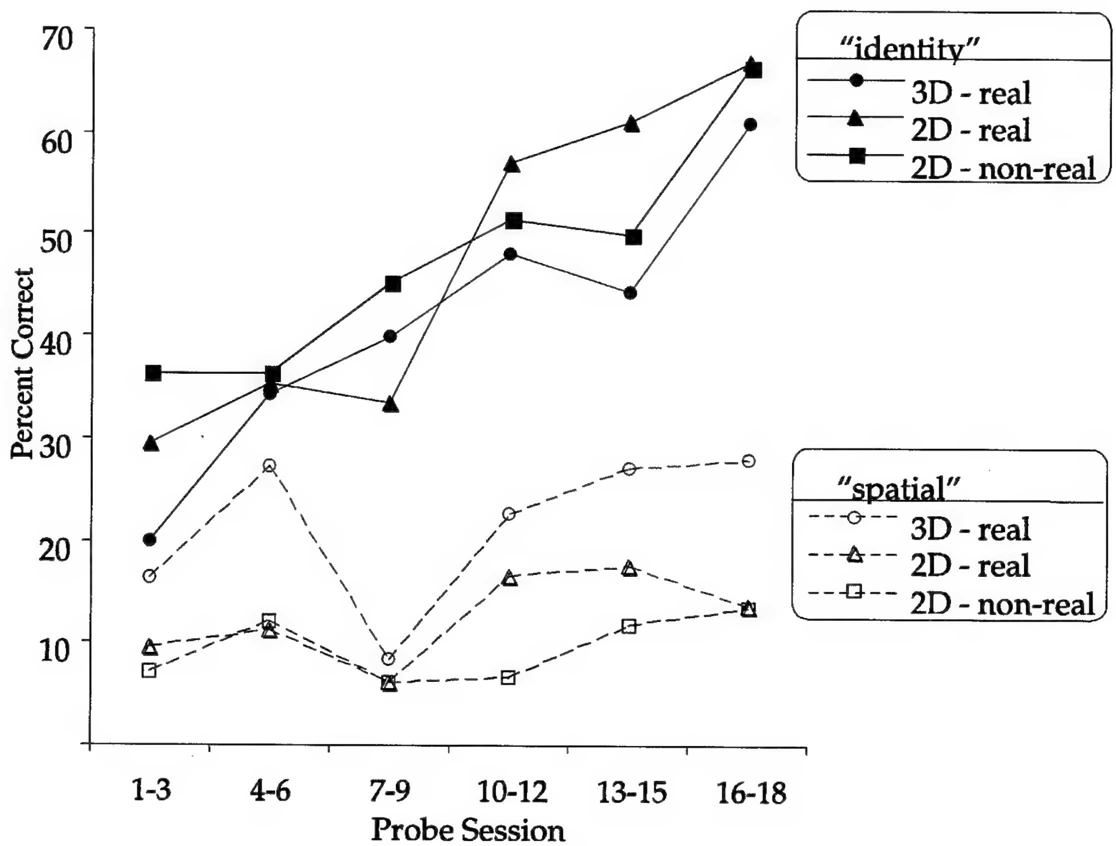

Figure 12. SA growth for identity attributes versus spatial attributes. Performance shown by probe session collapsed into six groups of three sessions.

DISCUSSION

Our objective was to test whether a 3-D perspective display for an AADC populated with realistic symbols would promote faster awareness of the surface and air track array attributes than an equivalent 2-D display. Our experimental design enabled us to find out whether any advantages were because of display format (2-D versus 3-D), symbol realism, or both. In general, 3-D perspective displays or realistic icons did not work any better than conventional 2-D displays or symbols. We found that 3-D SA grew faster but it started from a much lower level than 2-D SA. In fact, 3-D SA took 4 minutes to reach the start level of 2-D SA. However, 3-D was better than 2-D for some attributes. Likewise, realistic symbols supported better performance for some attributes than non-realistic symbols.

Altitude and attitude were remembered better in the 3-D condition. Attitude was easier for participants to recall when it was coded by an icon of a plane with its nose up or down and was more difficult to recall when participants had to hook the track to find out the same information. This replicates and extends the findings of Baumann et al. (1997) who had participants count the number of descending aircraft in a 3-D tactical display. They found that participants performed better using a 3-D display populated with realistic icons than in a conventional 2-D display.

In addition, we found that altitude was easier to understand when coded in 3-D. Altitude was coded explicitly in 3-D as the distance between a track symbol and its drop shadow on the groundplane. Altitude information was only accessible through hooking in the 2-D conditions. 3-D performance was surprisingly good when one considers that despite the explicit nature of altitude coding in 3-D, participants had two further cognitive steps involved in correctly gauging altitude. First, they had to correctly associate a symbol with its drop shadow and then estimate the distance between them. Second, they had to compare this estimate with the military altitude criteria of "high," "medium," or "low" to get the correct answer (Appendix A).

Realistic coding of heading was superior to symbolic coding of heading; heading is easier to remember when it is coded as an icon pointing in the track's direction. In the 2-D non-realistic condition, heading was depicted by a leader pointing in the heading direction protruding from an upright military symbol. Performance for the attribute of speed was the same for all conditions. This finding is not surprising because speed was coded using leader length for every condition.

An important finding of this study is that the key to making spatial attributes known is that they be visually explicit. This explicit visual coding may come from adding a third dimension (in the case of altitude and attitude) or from adding realism (in the case of heading). This finding is consistent with the expert who suggested that track attributes should be displayed "in some other visual way that more intuitively paints a picture" (Eddy et al. 1999).

There was some indication from the data (although not statistically significant) that symbolic track coding (i.e., identity attributes) was superior to realistic coding. The realistic symbol sets were difficult to learn. Participants made more errors and spent more time answering questionnaires about 2-D realistic symbols than 2-D non-realistic symbols. As participants had been equated for their subjective experience with military symbols, this was not the cause of the difference. Instead, it was more likely that the greater potential for confusion with the realistic icon set was responsible. For example, when depicted realistically, all aircraft icons have two wings and a fuselage, and all ships have elongated structures. Fine structural differences are hard to detect among these platforms and may not be visible from all viewpoints. Conversely, a non-realistic symbolic set such as the Mil-Std-2525B can be engineered for maximal discriminability. The identification of friendliness was easier for the Mil

Std. 2525 symbols because friendliness was double-coded by shape and color while in the realistic sets it was coded by color alone.

The participants also had great difficulty remembering tracks and track attributes from the scenario. Performance after 9 minutes of viewing the scenario was about 30 percent correct for all conditions. There is a growing body of perceptual literature highlighting how little information one assimilates from a scene despite one's impression to the contrary. For example, we are very insensitive to changes introduced into a scene after blanking it out momentarily (Rensink, O'Regan, and Clark, 1997). MacLeod and Willen (1995) put it best when they noted that the mother of all illusions is the illusion of perceptual objectivity. It appears that our participants spent most of their cognitive effort remembering track type and location, although they were given no instruction to do so by the experimenters. Over time, performance for the identity attributes increased twice as fast as the performance for the spatial attributes. Others have found that participants are most accurate at remembering the identity and location of air tracks shown in ATC scenarios, with the spatial attributes of heading and altitude being recalled worst (Mogford, 1997). Perhaps participants encode their memories of such scenes by identity first (e.g. "there was a fighter over there, now where was it going?").

In conclusion, our 3-D perspective display populated with realistic symbols did not provide faster awareness of overall track attributes than the equivalent 2-D display. Location and attributes of tracks were learned quicker during the first 4 minutes with the 2-D top-down display with non-realistic symbols than with the displays using the realistic symbols (2-D or 3-D). However, after 9 minutes the 2-D and 3-D displays with the realistic symbols provided superior SA for track heading and approached the overall SA found with the 2-D display with non-realistic symbols. The 3-D display also provided superior SA for track altitude and attitude.

SUMMARY

- Participants became increasingly aware of the identities of tracks over time, but they had difficulty remembering the spatial attributes of those tracks.
- 2-D SA was initially 2.5 times higher than 3-D SA and remained significantly higher for the first 4 minutes.
- 3-D SA increased six times faster than 2-D SA for the first 5 minutes.
- Overall SA was equivalent for 2-D and 3-D after 9 minutes.
- 3-D was superior to 2-D for the attributes of altitude (4 times) and attitude (20 times).
- Realistic symbols were superior (two times) to non-realistic symbols for the heading attribute.
- Participants found it harder to learn realistic symbology.

We conclude:

- 2-D top-down display with conventional (non-realistic) symbols provided superior SA during the first 4 minutes.
- 3-D displays with realistic symbols provided superior SA for altitude, attitude, and heading attributes.

RECOMMENDATIONS

- Consider using 2-D top-down displays with conventional (non-realistic) symbols when very rapid SA is necessary.
- Consider using 2-D or 3-D realistic symbology when rapid heading appreciation is necessary.
- Consider using 3-D displays when rapid altitude and attitude appreciation outweighs other factors.

In the introduction, we reviewed the relative merits of 2-D and 3-D displays. Based on that review and the experience we gained during this project, we offer the following broad recommendations:

- Perspective view displays should be used judiciously for tasks that show significant user SA performance enhancements because absolute certainty about two dimensions is lost by adding in the third dimension.
- Consider using both a 2-D and a 3-D display of the same information to optimize the benefits of each.
- Consider improving the 2-D display with explicit visual coding of attributes without hooking to get pop-up text boxes, which is time consuming. An important consideration in the choice between 2-D and 3-D is accurately locating a platform in time and space, which is a highly critical attribute that was not evaluated for the 3-D display in this study. 2-D top-down displays with conventional (non-realistic) symbols provide accurate perceptions of platform location.

The 3-D display engineering could improve in two other ways: (1) make the realistic symbols more discernable, and (2) provide recommendations for users on how they might maneuver their viewpoint in 3-D to minimize poor perception of far distances and the clutter effects.

Our future research will focus on perception accuracy of 3-D platform location using drop lines, shadows, and relative size as cues. The outcome of this follow-on study could strongly affect any recommendation for introducing 3-D displays into the AADC console.

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APPENDIX A

The air tracks were classified as high, medium, or low as an altitude function (feet) in a realistic military context. For example, a bomber at a 14,000-ft altitude is considered low although it is physically higher than an attack helicopter, which, at 6000 ft is considered high. This military context was explained to participants with a poster depicting the graphic (for 3-D realistic) condition in figure A-1.

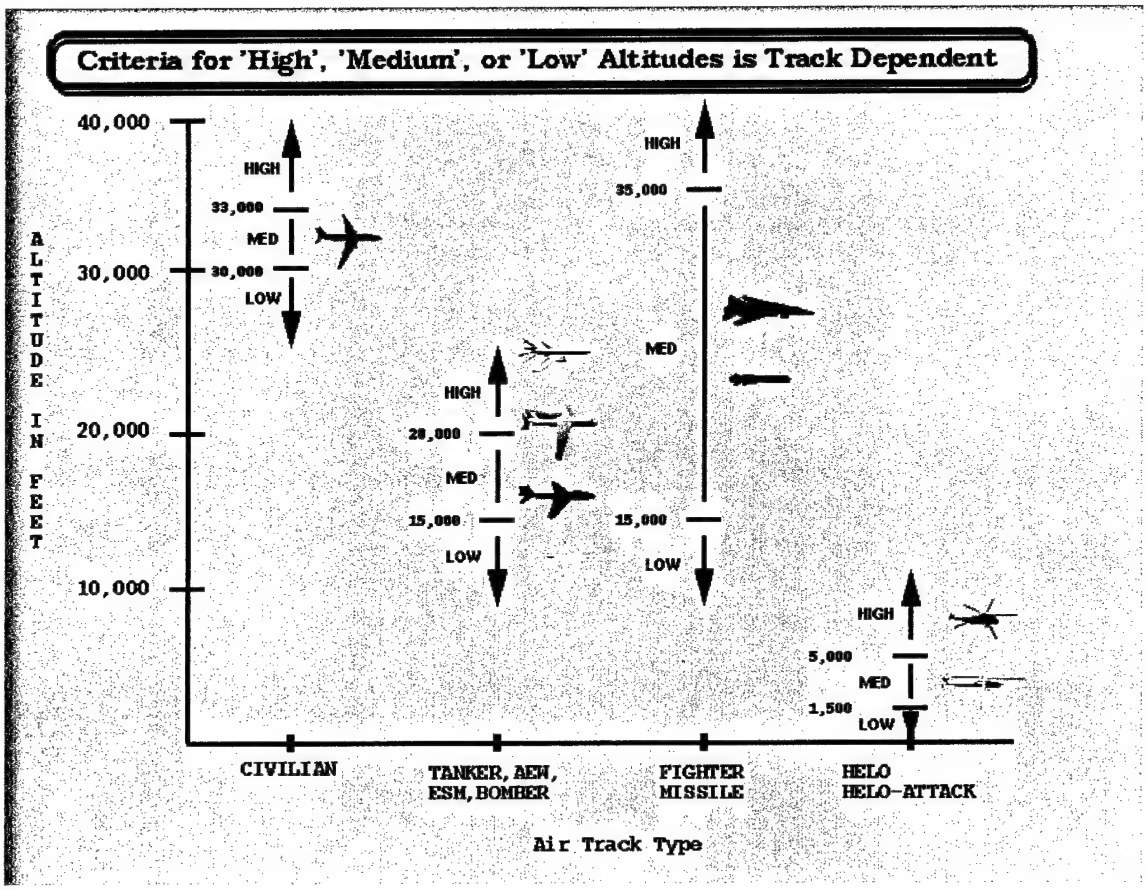

Figure A-1. Altitude was coded in a track-dependent way for military realism. Graphic shown to participants in 3-D real condition.

APPENDIX B

Figure B-1 shows a screenshot of the questionnaire that participants filled out on the computer to indicate their awareness of probed track attributes. In this case, the participant is filling out the responses to the first probed item (one out of four). The participant has described the track as an air track, specifically a bomber, of unknown friendliness (Force ID), at a high altitude, with medium speed and level attitude heading south. When the participant has completed as much as possible for each of four questionnaires, the "submit all screens" button (bottom right) is pressed and the scenario is resumed until the next probe session.

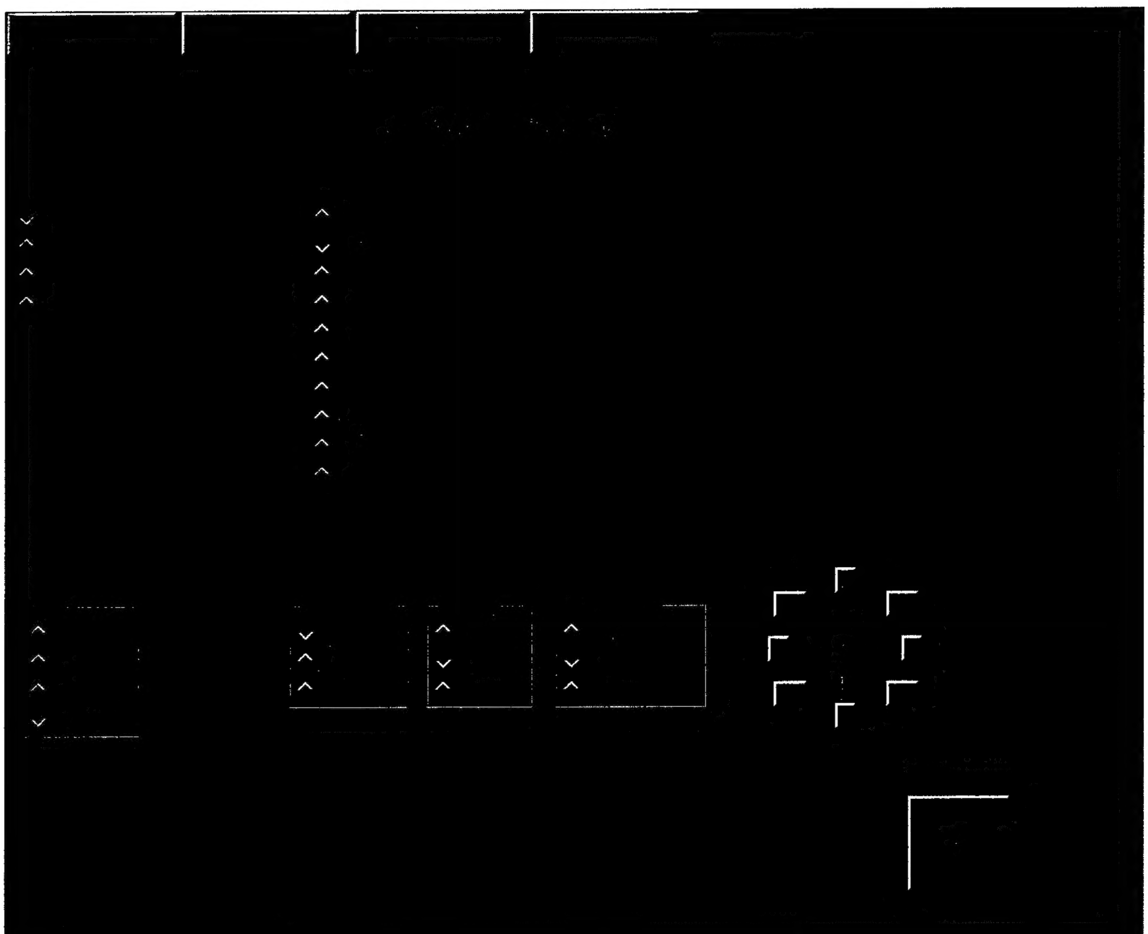

Figure B-1. Screenshot of questionnaire to indicate awareness of probed track attributes.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1999

3. REPORT TYPE AND DATES COVERED
Final: October 1997 to March 1999

4. TITLE AND SUBTITLE
DESIGNING A DISPLAY FOR THE AREA AIR DEFENSE COMMANDER
The Role of 3-D Perspective Views and Realistic Track Symbols in Achieving Rapid Situation Awareness

5. FUNDING NUMBERS
C: N66001–96–D–0048
PE: 0602233N
AN: DN309119
WU: CDB8

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SSC San Diego
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER
TR 1803

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space and Naval Warfare Systems Command
PMW–467
4301 Pacific Highway
San Diego, CA 92110

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Area Air Defense Commander (AADC) plans, coordinates, and executes air defense operations in a theater of operations. This responsibility requires a clear tactical picture of friendly and hostile forces and their capabilities. A new display has been prototyped for this purpose. This prototype display has a three-dimensional (3-D) perspective format and uses novel volumetric (realistic) symbols. It has been touted as enabling users to become more rapidly aware of the tactical picture than a comparable two-dimensional (2-D) display. This study addresses two questions:

1. Does the 3-D display format promote more rapid Situation Awareness (SA) than a conventional 2-D display format?
2. Do the new detailed 3-D volumetric realistic symbols enhance performance over their more conventional counterparts?

Three participant groups observed a 9-minute scenario in three different ways. The first group saw the scenario in a 3-D perspective view with realistic symbols. The second group saw a 2-D top-down view with realistic symbols. The third group saw a 2-D top-down view with conventional (non-realistic) symbols. The scenario was stopped every 30 seconds in each condition and an online questionnaire assessed participant SA attributes of depicted tracks.

The authors conclude that the 2-D top-down display with conventional (non-realistic) symbols provide superior SA during the first 4 minutes and that 3-D displays with realistic symbols provide superior SA for altitude, attitude, and heading attributes. Based on this study, the authors recommend that designers consider using 2-D top-down displays with conventional (non-realistic) symbols when very rapid SA is necessary, 2-D or 3-D realistic symbology when rapid heading appreciation is necessary, and 3-D displays when rapid altitude and attitude appreciation outweighs other factors.

14. SUBJECT TERMS
Mission Area: Command, Control, Communications
3-D display
situation awareness
virtual environments
man–machine interface
perception

15. NUMBER OF PAGES
46

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

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